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PSpice Simulation of Atmospheric Pressure Air Glow Discharge Plasma Applicator Systems

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Abstract – **Electrical characteristics of an Atmospheric Pressure Air Glow (*APAG*) discharge plasma applicator system have been simulated by using commercial circuit simulation software such as PSpice®. A plasma applicator system integrally includes a power supply, transformer, impedance matching network, and plasma applicator. A PSpice® model has been developed for the plasma discharge in an *APAG* discharge applicator, which consists of two parallel electrode plates with a small gap between electrodes. At least one of the electrodes is covered by a dielectric barrier.**

An *APAG* discharge plasma applicator can be modeled as an electric capacitor without plasma, and as an air gap containing plasma. The cold plasma itself has been modeled as a voltage-controlled current source that switches on when the voltage across the air gap exceeds the value of the discharge ignition or plasma initiation voltage.

The simulation results agree with experimental data from actual applicators. It has been found that in different operating regimes, the discharge current of the *APAG* discharge plasma applicator is described by a voltage linear law.

Keywords – **Atmospheric pressure air glow (*APAG*) discharge, cold plasma, one-atmosphere glow discharge, discharge ignition voltage, voltage-controlled current source, current-voltage behavior, parallel-plate and coplanar discharge plasma applicators**

I. INTRODUCTION

Atmospheric pressure air glow (*APAG*) discharges, or *dielectric-barrier* (simply *barrier* or *silent*) *discharges*, have been well known for more than a century. First experimental investigations concentrated on the generation of ozone were reported by *W. Siemens* (1857). A few years after Siemens' original publication, *T. Andrews* and *P. Tait* (1860) proposed the name "*silent discharge*" (*stille Entladung*, *décharge silentieuse*) which is still used frequently in the English, German, and French scientific literature, [1].

J.-R. Roth introduced, on the base of the observed phenomenological characteristic of the normal glow discharge voltage-current behavior, the name "*one-atmosphere uniform glow discharge*" (*OAUGD*). Other cases of such behavior have been often reported in the contemporary literature. The normal glow discharges, as the dielectric-barrier discharges, ignite and burn at constant discharge ignition (or burning) voltage, [2].

The characteristics of many electrical systems can be simulated with proprietary computing tools such as *PSpice*®. Devices employing cold plasmas are embedded in electrical systems in many situations. It is advantageous to simulate the complete system, including the plasma as phenomena, with such commercial software. Previous papers concerning the computational simulation of high pressure plasma in air discharge were investigated, [3, 4].

Normally, the *APAG* discharge plasma applicator (or reactor) system for plasma-chemical modification (or functionalization) of low energy surfaces consists of a power supply, transformer, impedance matching network, and plasma applicator. This electrical system was an object of simulation with such computational tools, Fig. 1.

In an electrical discharge system, the inductors and capacitors, in the impedance matching network, the power supply, and the transformer are ordinary electrical components and have well-developed *PSpice* models. However, as there is no available electrical model in *PSpice* for the plasma discharge in an *APAG* discharge plasma applicator, to develop such a model is a principal simulation task, [3, 4, 6].

In this paper, specific circuit *PSpice* models of *APAG* discharge plasma parallel-plate and coplanar applicator systems have been obtained with the proprietary circuit simulation software *PSpice* and compared with experimental data.

II. PSPICE MODELS FOR PARALLEL-PLATE AND COPLANAR *APAG* DISCHARGE PLASMA APPLICATORS

A parallel-plate *APAG* discharge plasma applicator consists of two parallel metal electrode plates, one or two dielectric plates (barriers) with one or two small air gaps between barriers and electrodes. At least one electrode is covered with a dielectric plate or coating, as shown in Fig. 2.

Coplanar *APAG* discharge plasma applicators consist of a flat panel with multiple coplanar plasma electrode strips alternating in polarity, and with each polarity connected in parallel. The flat panel consists of a thin dielectric plate either with electrode strips on one or both sides, or with electrode strips on one side and a metallic electrode sheet on the other. When a voltage is applied across a flat coplanar panel, a planar plate plasma layer is generated either on both sides of the dielectric or only on the side having the electrode strips, depending on the electrode configuration.

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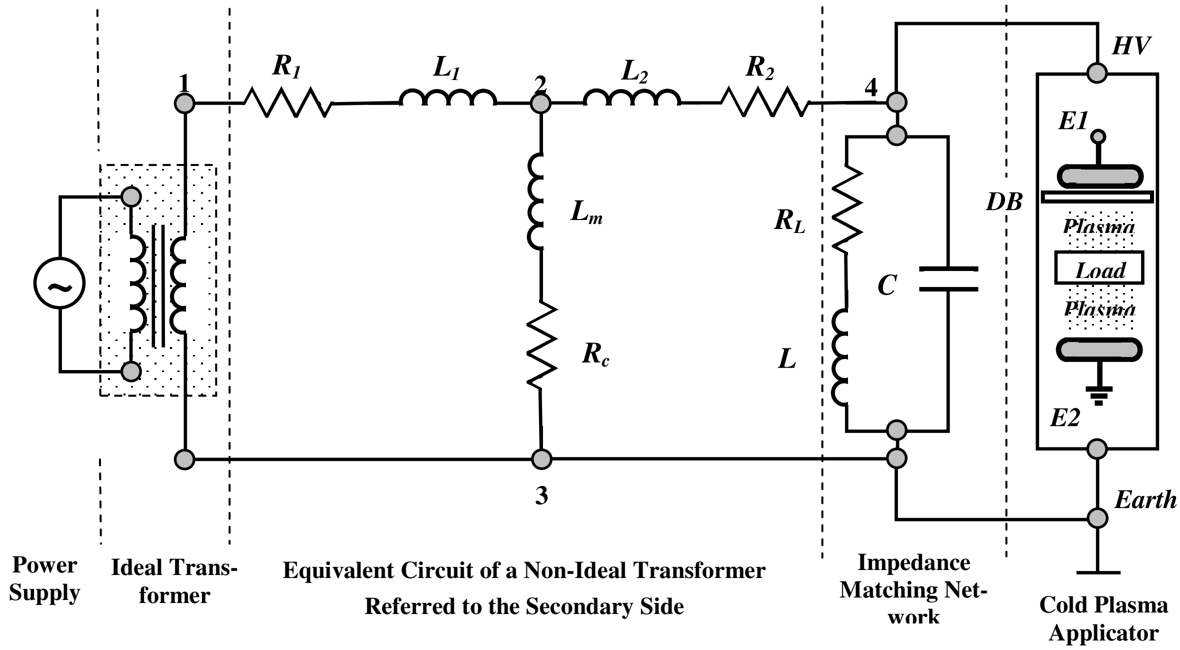

Fig. 1. Schematic presentation of an *APAG* discharge plasma applicator system for *PSpice* circuits simulation

Since the plasma generated on both sides of the coplanar plasma applicator systems, Fig. 3a, resembles the plasma in two-operating-gap parallel-plate applicators, Fig. 2c, we can construct a *PSpice* model for coplanar applicators based on the model for parallel-plate applicators.

Since the plasma energized on one of the sides of the coplanar plasma applicators, Fig. 3b, resembles the plasma in one-dielectric-barrier parallel-plate applicator systems, Fig. 2b, we can also construct a *PSpice* model for coplanar applicators based on the model for parallel-plate applicators.

Z. Chen provides a general plasma circuit *PSpice* simulation model – that of a one-dielectric-barrier discharge plasma applicator, which consists of one operating gap, capable of incorporation into circuit simulations, Fig. 2 [3].

The *PSpice* model for the dielectric plate or coating can be modeled as a capacitor with high parallel resistance, as can the gap containing the cold plasma. Based on the phenomenology of normal glow discharges and *APAG* discharges, Fig. 2, the *APAG* discharge plasma itself can be modeled as a voltage-controlled current source that is switched on as long as the voltage across the operating gap exceeds the value of the discharge ignition voltage [3].

The current source and its output current vary in accordance with a power law of the applied voltage. *R. Gadri* shows that an atmospheric *RF* glow discharge in helium exhibits the same phenomenology as low-pressure *DC* glow discharges.

J. Roth reported that the current-voltage (I-U) behavior of the high-power glow discharge was $I \propto U^2$, and $I \propto U^3$, depending on the operating regime:

$$I \begin{cases} =0,\ for\ V_g < V_{pi} \\ \alpha\left(U_g - U_{pi}\right)^n,\ for\ V_g > V_{pi} \end{cases} \quad , \tag{1}$$

where n is an integer that ranges from 1 to 12 in different glow discharge plasma devices, [3].

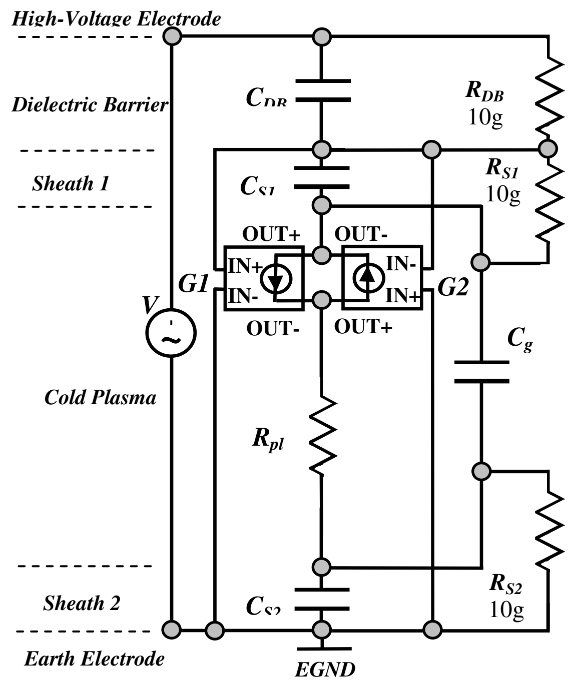

Fig. 2. General model for an *APAG* discharge plasma applicator system (with one dielectric barrier) for *PSpice* circuits simulation - *Roth-Chen*'s model

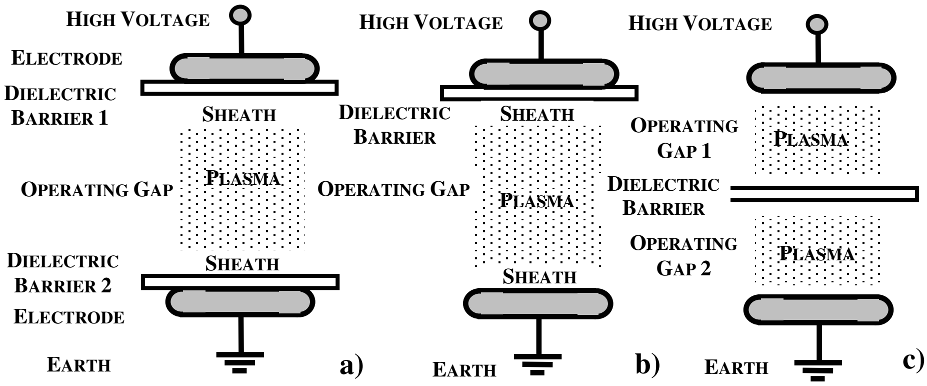

Fig. 3. Parallel-plate *APAG* discharges plasma applicators: **a** – two-dielectric-barriers discharge plasma applicator; **b** – one-dielectric-barrier discharge plasma applicator; **c** – two-operating-gap plasma applicator.

III. NEW PSPICE MODEL FOR *APAG* DISCHARGE PLASMA APPLICATOR SYSTEMS

The adopted simulation of an *APAG* discharge plasma applicator by using the *Roth-Chen's schematic* model, Fig. 2, has demonstrated some negative aspects: for instance, the presence of indeterminacy when the voltage applied across the operating gap is equal to the critical ignition voltage: $U_g < U_{pi}$; negative values of current I at $n = 2\text{ k} - 1$ (odd number); unstable operation of the simulator due to indeterminacy (the upper and lower limits of the variation range are not fixed) of the difference $(U_g - U_{pi})^n$; the ignition current is never equal to zero – it has an exactly determined critical value $I_{cr} > 0$ [4].

All this required the creation of a new *PSpice* schematic model for an *APAG* discharge plasma applicator, which is governed by the following general relationship reflecting the stationary burning regime of an *APAG* discharge [3]:

$$\text{(2)} \qquad \begin{cases} I_{av} - I_{cr} = 0 \ \ for\ U_{eff} < U_{cr} \\ I_{av} - I_{cr}\ \alpha \left(U_{eff} - U_{cr}\right)^n \ \ for\ U_{eff} > U_{cr} \end{cases},$$

where $U_{cr} > U_{br}$ (U_{br} is the discharge burning voltage) and I_{cr} are the critical parameters of ignition of an *APAG* discharge.

The simulation model (schematics) is constructed on the basis of using a dependent current source GVALUE (from the library abm.slb - *Analog Behavioral Models*), for which the control may be preset as a mathematical expression connecting the output current and the input variable – an *e.m.f.* formed at the output of another dependent *e.m.f.* source EVALUE, for which the control is also preset as an analytical expression relating the input voltage U_g - ΔU_b, where ΔU_b is the voltage drop across the barrier, to the controlling GVALUE *e.m.f.,* Fig. 5.

Controlling the dependent current sources *G1* and *G2*, one for each half-wave of the harmonically varying voltage of the ideal voltage source *V*, is realized by the dependent *e.m.f.* sources *E1* and *E2* in accordance with Eqn. 2, introducing the value of the critical ignition voltage U_{cr} of the discharge.

The limiting element LIMIT with parameters 0 and 500 is placed at the output of dependent voltage sources. The upper limit is in conformity with the maximal real values that can be assumed by the difference $(U_g - U_{cr})^n$, (voltage is in kV).
The model behavior in time (*Transient Response*) as a reaction to the application of a voltage across the electrodes, which varies with different frequency (50 Hz, 10 kHz, 30 kHz) in time, is investigated.

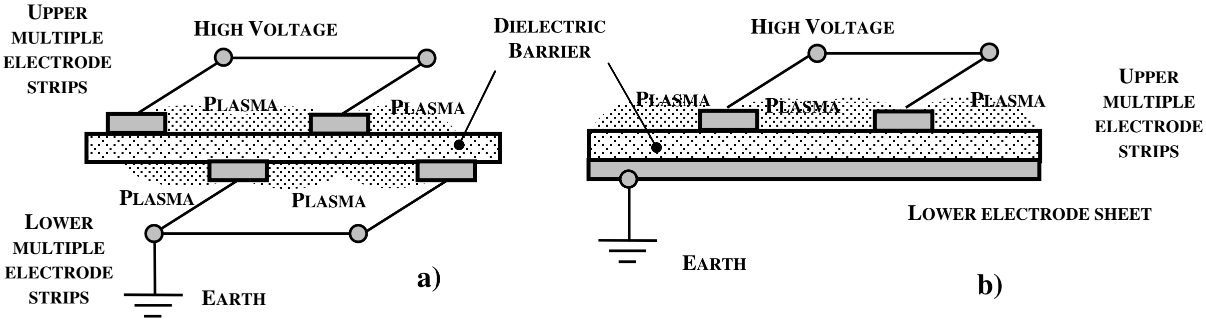

Fig. 4. Coplanar *APAG* discharge plasma applicators: **a** – two-multiple-planar-electrode-strips plasma applicator, or two-(upper and lower)-side plasma-energized applicator; **b** – one-multiple-planar-electrode-strips plasma applicator, or one-(upper)-side plasma-energized applicator.

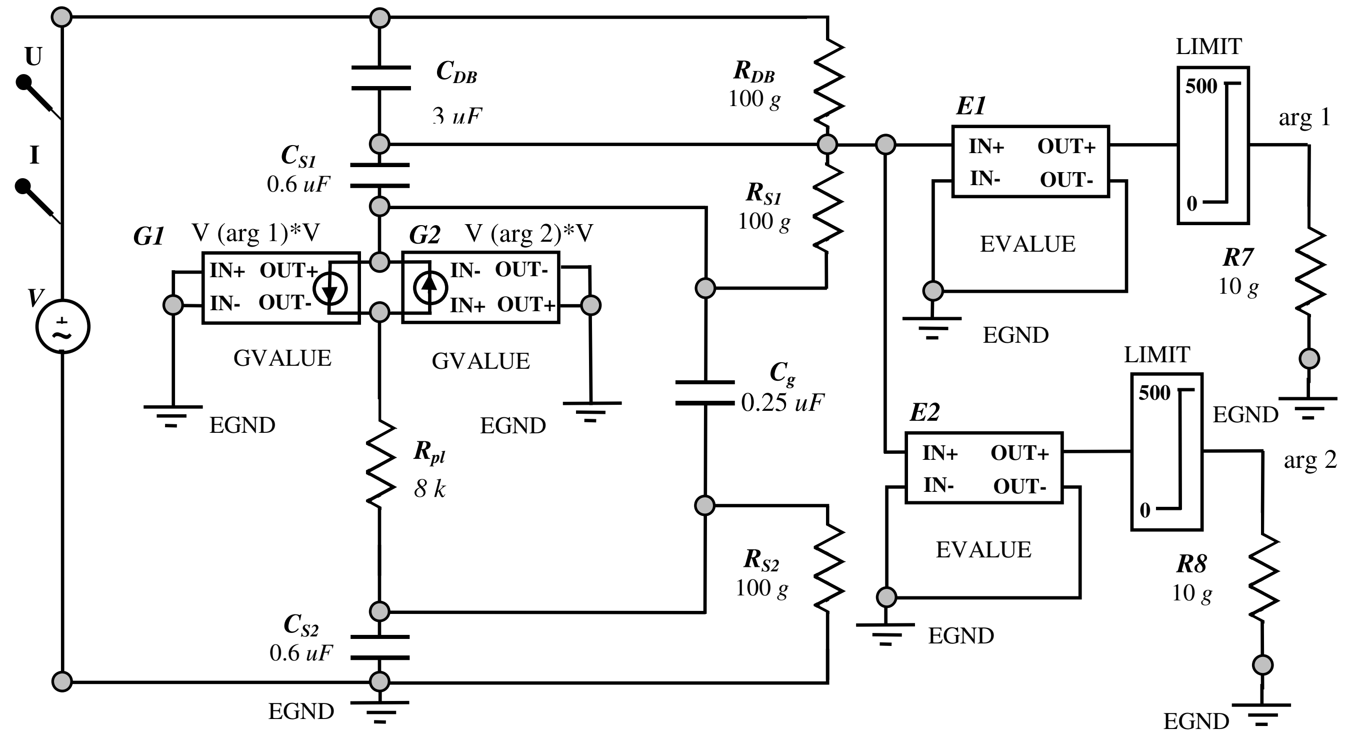

Fig. 5. New *PSpice* circuits simulation model for an *APAG* discharge plasma applicator system (with one dielectric barrier)

IV. Discussion and Conclusion

The simulation verifies that the amplitude of the simulated discharge current is determined by four independent variables - the values of the critical parameters - the voltage U_{cr} and current I_{cr} of ignition**;** the dielectric barrier capacitance, and the applied voltage across the electrodes. It has been found, too, that the power-law exponent n has a minor effect on the modeled discharge current waveform, Fig. 6.

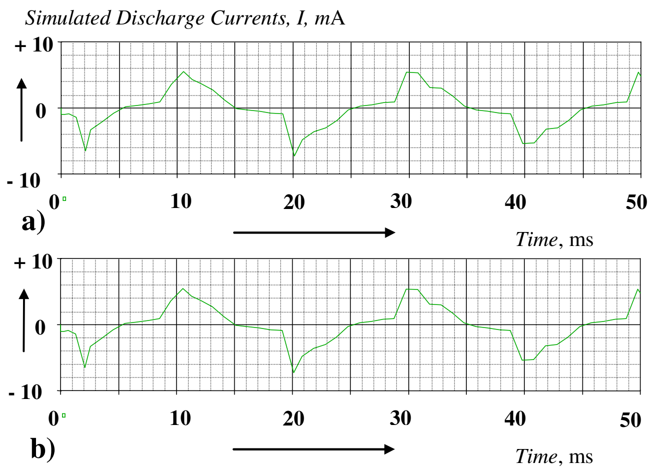

Fig. 6 – Comparison of the simulated discharge currents for an *APAG* discharge plasma applicator system (with one dielectric barrier) with different power-law exponent: **a** - n = 1.4; **b** - n = 12 (U_{eff} = 20 kV; δ_{bar} = 3 mm; δ_{gap} = 3mm).

We have developed a satisfactory PSpice circuit model for *APAG* discharge plasma applicator systems.

Acknowledgement

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